International Colloquia on
Thermal Innovations

Five Grand Challenges in Thermal Science and Engineering for Deep Decarbonization

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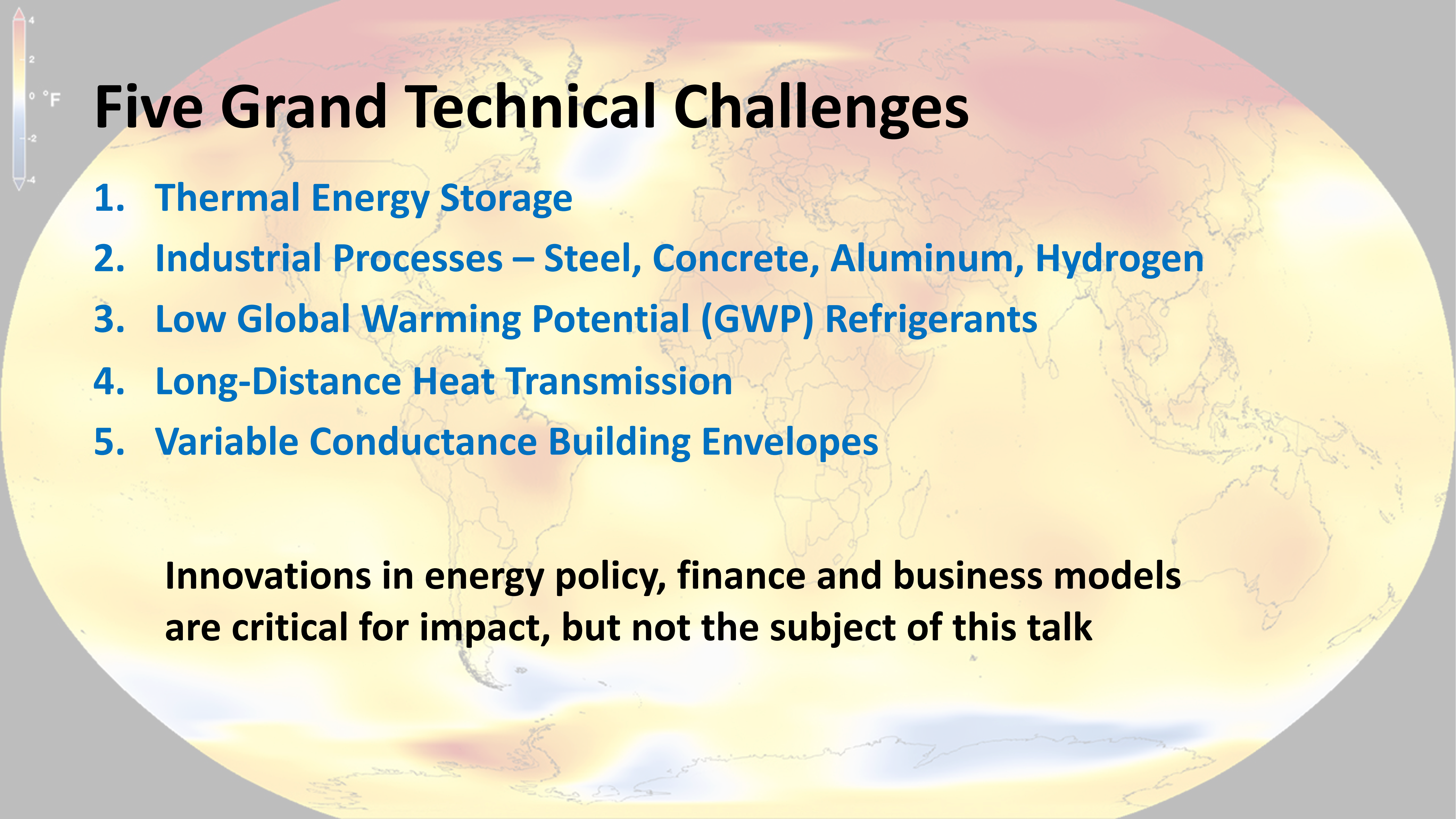
Acknowledgements:
Asegun Henry (MIT), Ravi Prasher (LBL/UC Berkeley)

Sponsored by: MITMECHE

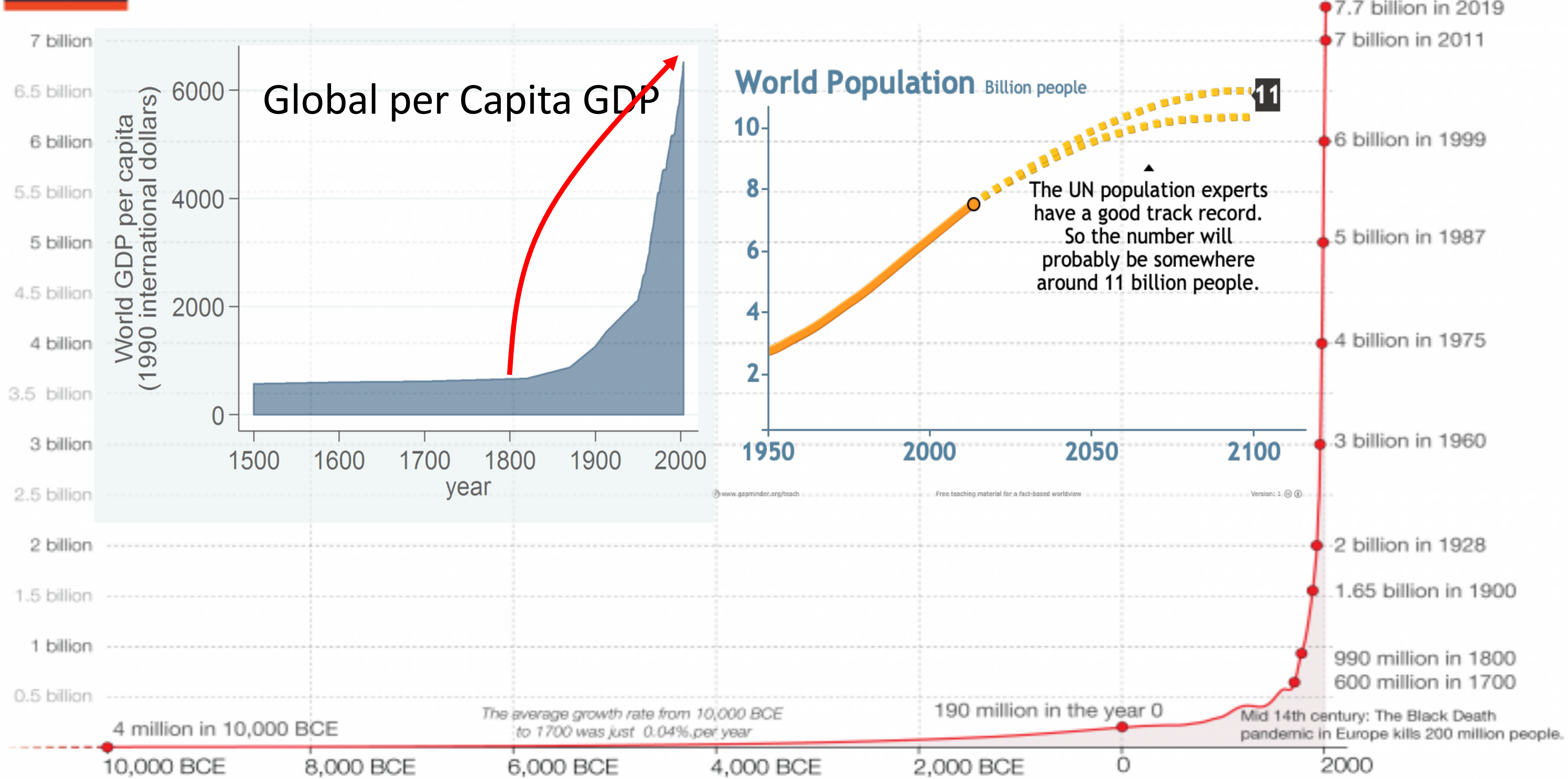


Five Grand Technical Challenges

1. Thermal Energy Storage
2. Industrial Processes – Steel, Concrete, Aluminum, Hydrogen
3. Low Global Warming Potential (GWP) Refrigerants
4. Long-Distance Heat Transmission
5. Variable Conductance Building Envelopes

Innovations in energy policy, finance and business models are critical for impact, but not the subject of this talk

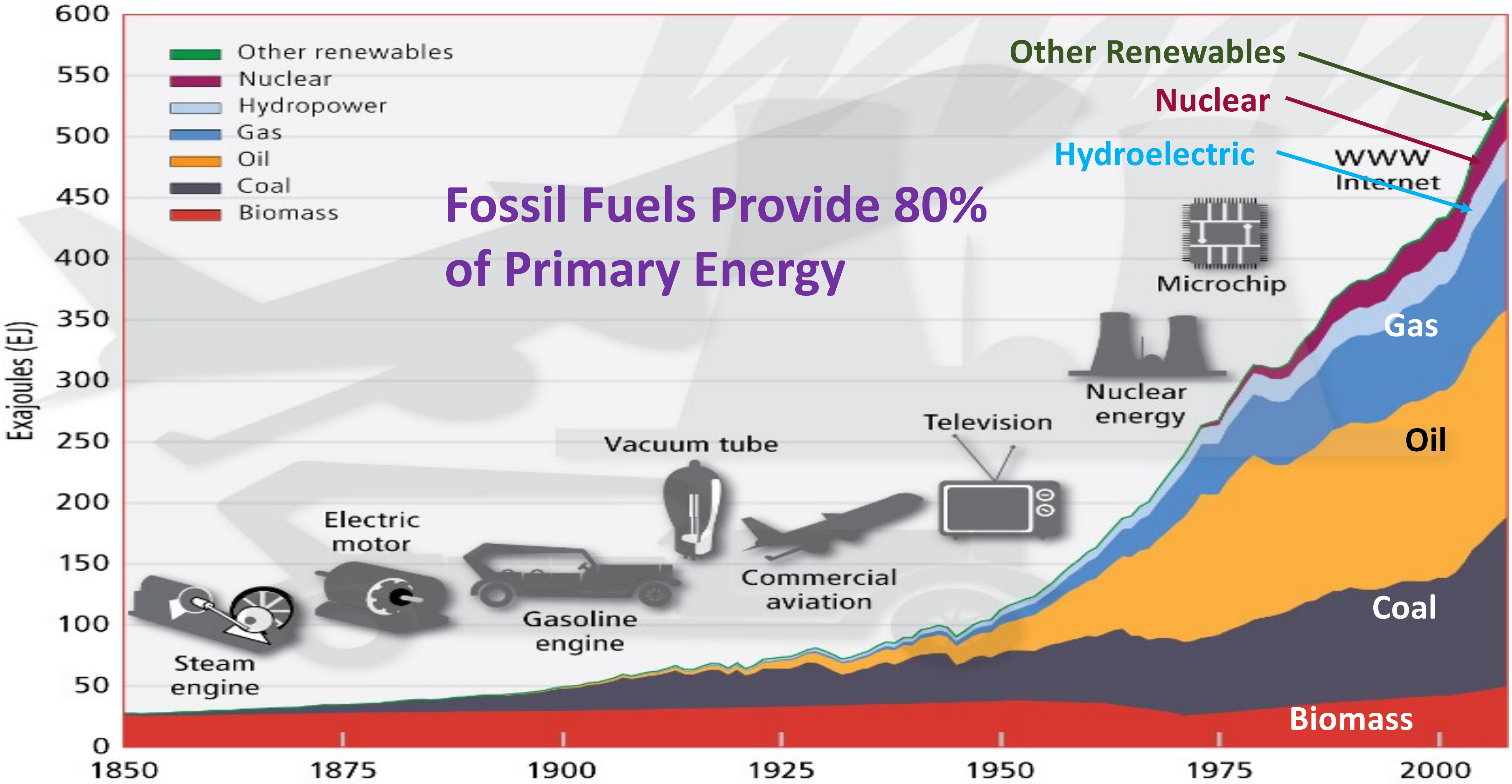
The size of the world population over the last 12.000 years



Based on estimates by the *History Database of the Global Environment* (HYDE) and the United Nations. On OurWorldinData.org you can download the annual data.

This is a visualization from OurWorldinData.org, where you find data and research on how the world is changing.

Energy is essential for economic growth and quality of human life

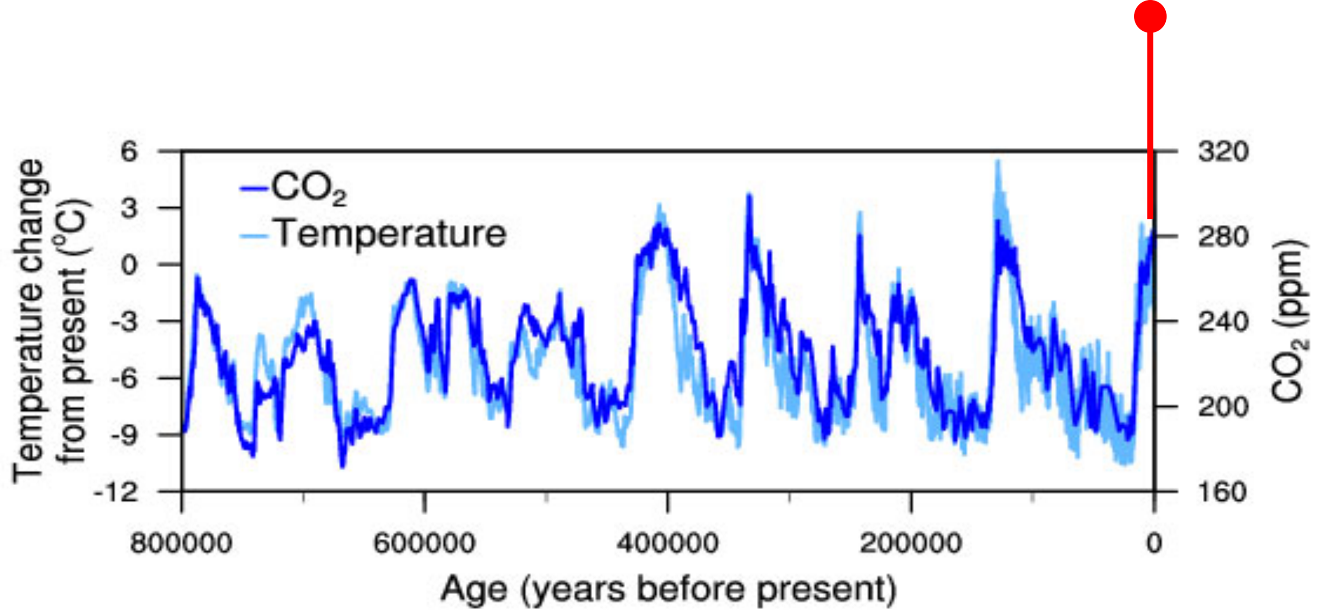


Other Renewables

Nuclear

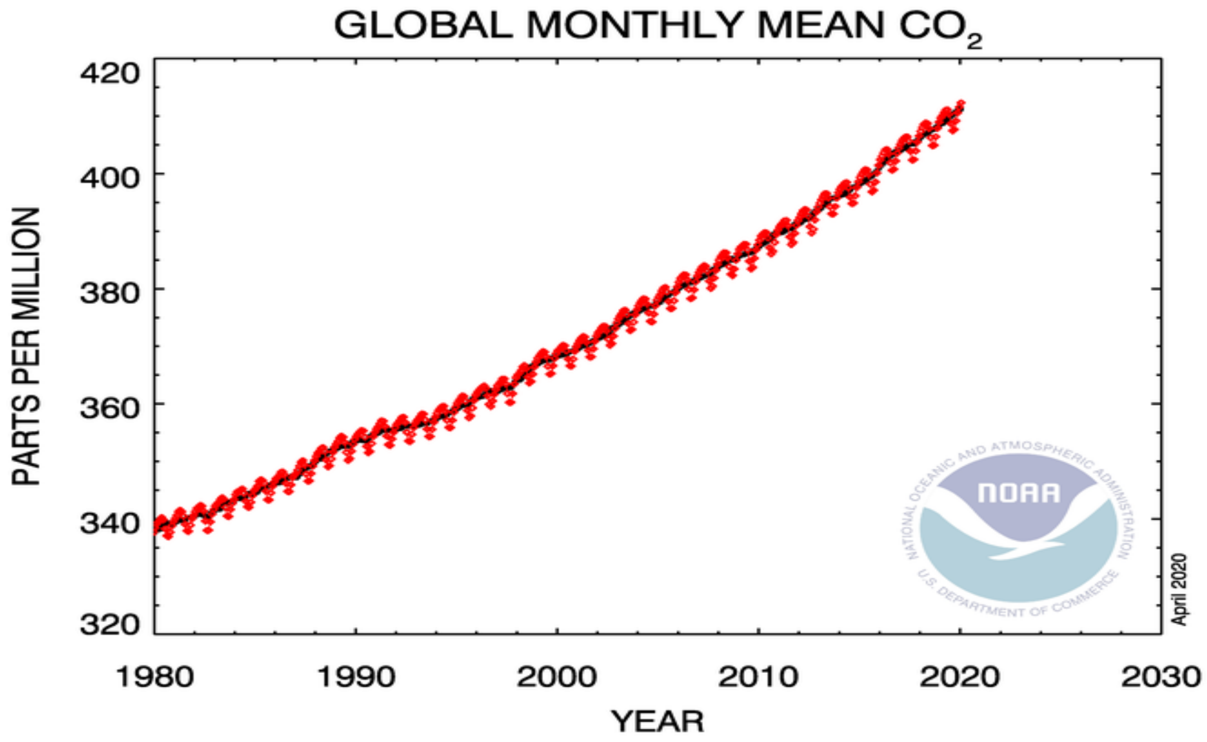
Hydroelectric

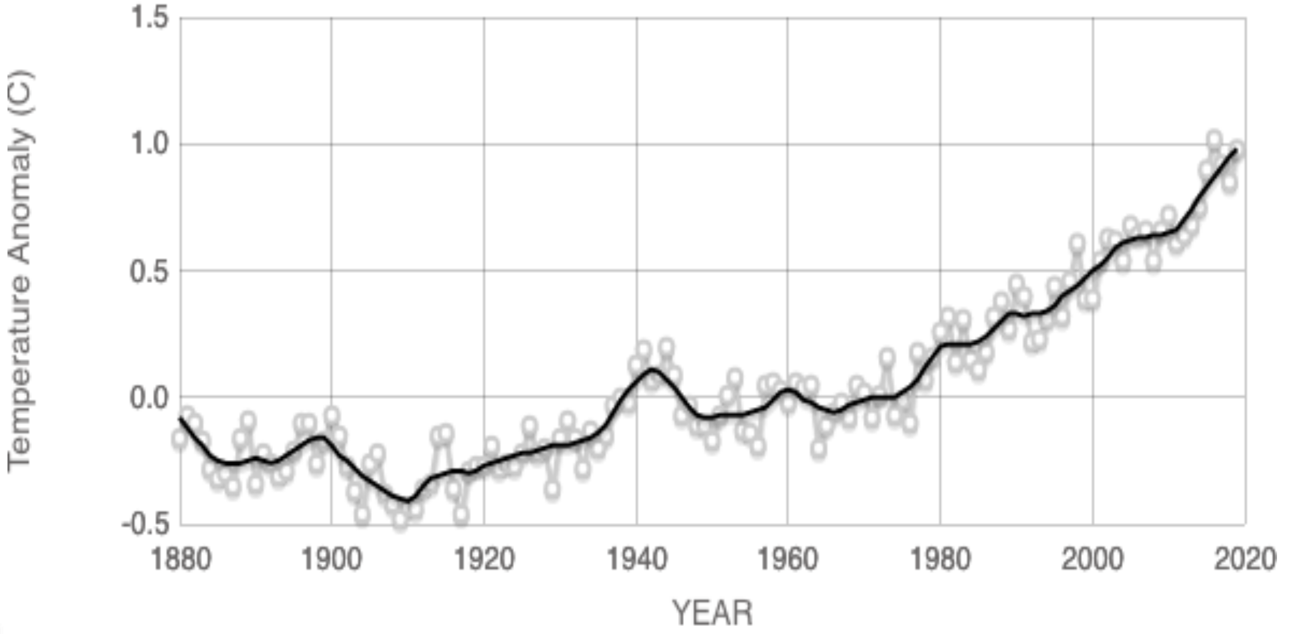
Fossil Fuels Provide 80% of Primary Energy



Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J.-M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T.F. Stocker. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, Vol. 453, pp. 379-382, 15 May 2008

2.0 °C →


GLOBAL MONTHLY MEAN CO_2



Source: climate.nasa.gov

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ENERGY

Quiz

Defining Dual Challenge of 21st Century
- Providing access to affordable and secure energy for economic growth
- Reducing greenhouse gas emissions

1 °C

2 °C

1000 $GtCO_2$ - 70% probability for < 2 °C

40 $GtCO_2$/year – increasing at 1%/yr

20-30 years

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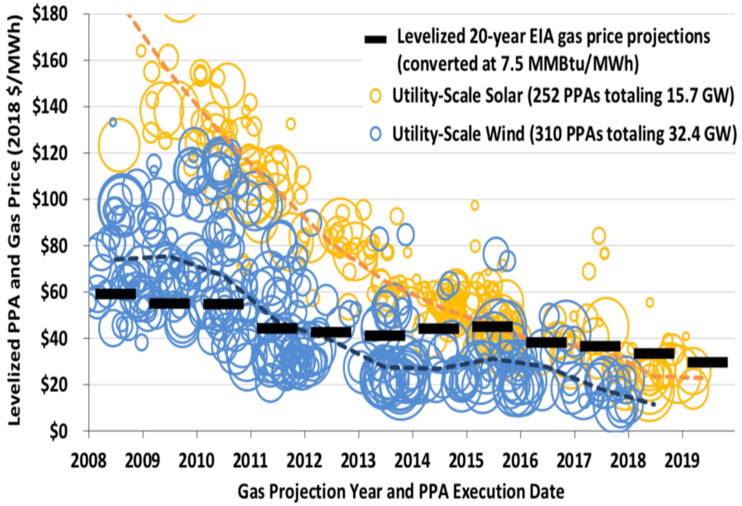
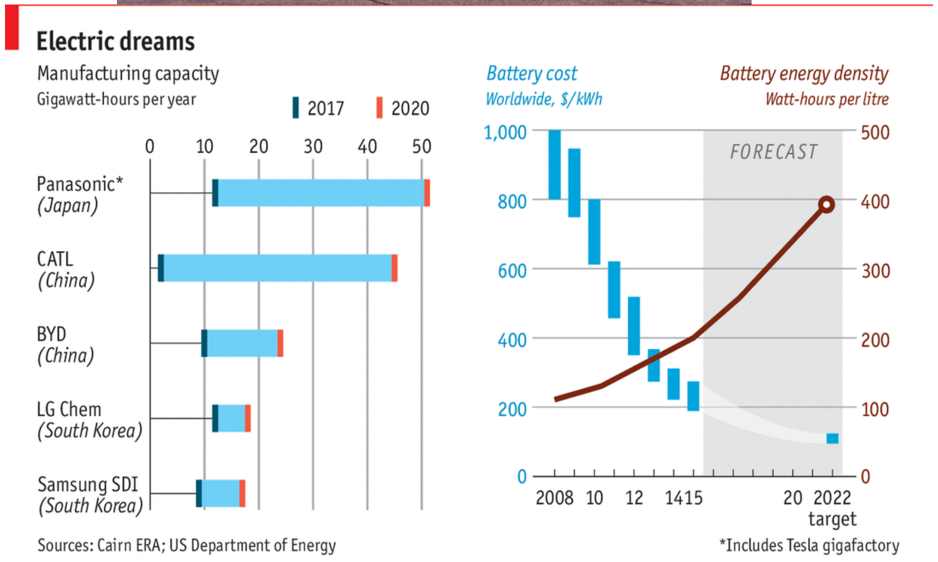
ENERGY

Gamechangers

Modern Renewables Produce Most Inexpensive Electricity, But Intermittent



Lithium-Ion Batteries Will Likely Make Electric Vehicles Range & Cost Competitive with Gasoline Cars ≤ 2025



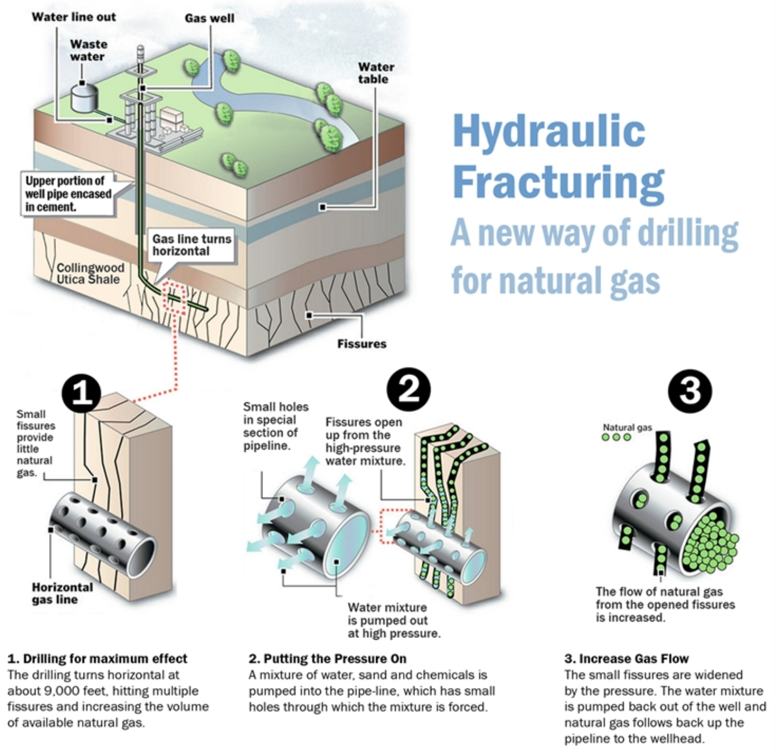
Electric dreams

Sources: Cairn ERA; US Department of Energy

*Includes Tesla gigafactory

Economist.com

Unconventional Gas is Inexpensive and Abundant – Replacing Coal



Hydraulic Fracturing
A new way of drilling for natural gas

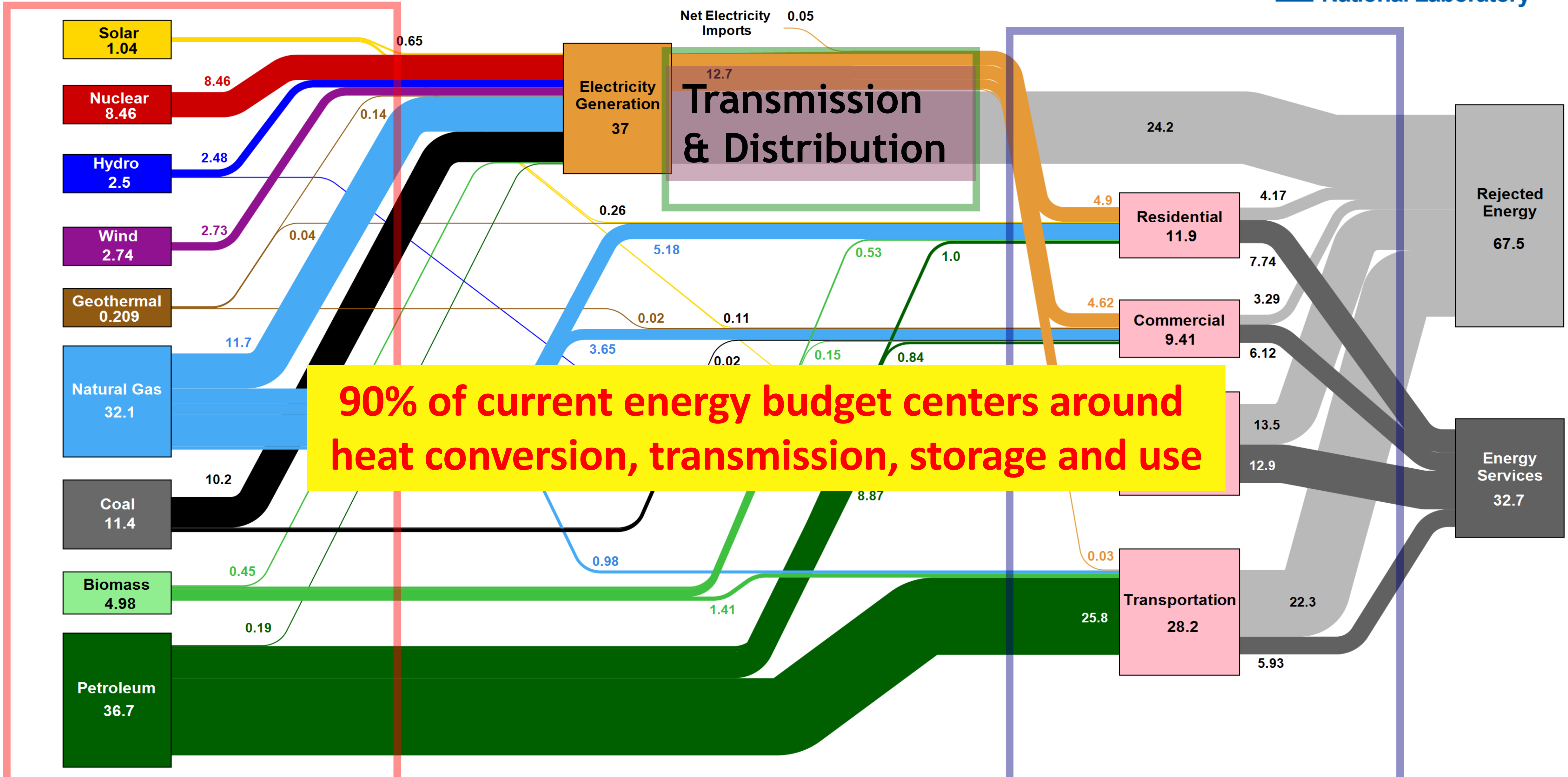
1. Drilling for maximum effect
The drilling turns horizontal at about 9,000 feet, hitting multiple fissures and increasing the volume of available natural gas.

2. Putting the Pressure On
A mixture of water, sand and chemicals is pumped into the pipe-line, which has small holes through which the mixture is forced.

3. Increase Gas Flow
The small fissures are widened by the pressure. The water mixture is pumped back out of the well and natural gas follows back up the pipeline to the wellhead.

Estimated U.S. Energy Consumption in 2019: 100.2 Quads

Lawrence Livermore National Laboratory



Transmission & Distribution

90% of current energy budget centers around heat conversion, transmission, storage and use

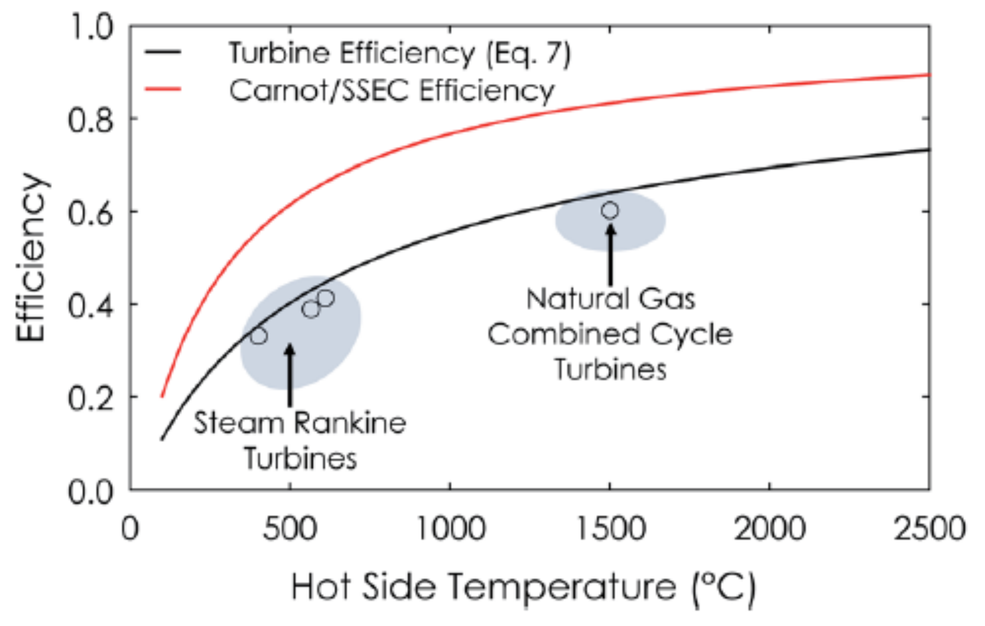
Supply

Demand

Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Five Grand Challenges that have Highest Opportunity for Impact

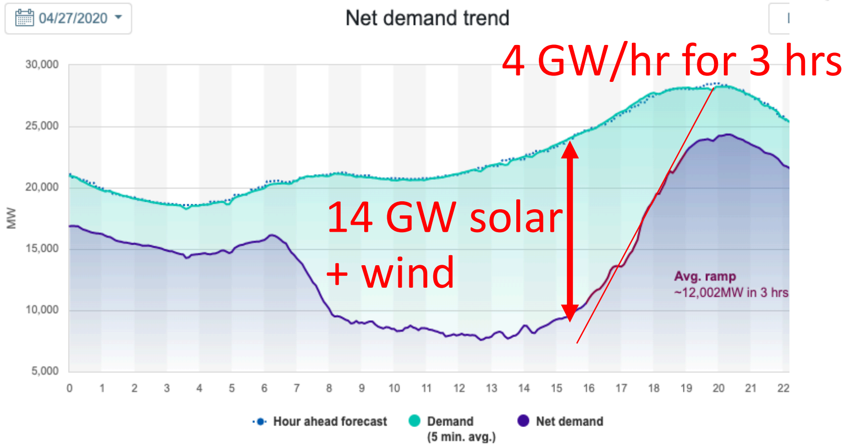
1. **Thermal Energy Storage**
2. **Industrial Processes – Steel, Concrete, Aluminum, Hydrogen**
3. **Low Global Warming Potential (GWP) Refrigerants**
4. **Long-Distance Heat Transmission**
5. **Variable Conductance Building Envelopes**



A. Henry, RS Prasher, “The prospect of high-temperature solid state energy conversion to reduce the cost of concentrated solar power,” *Energy & Env Sci* **7**, 1819 (2014)

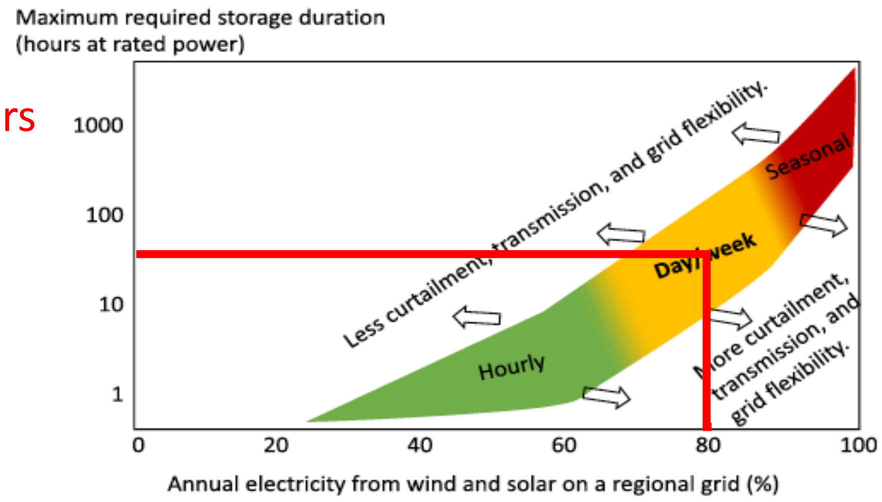
Energy Storage Needs

California Daily Electricity Demand

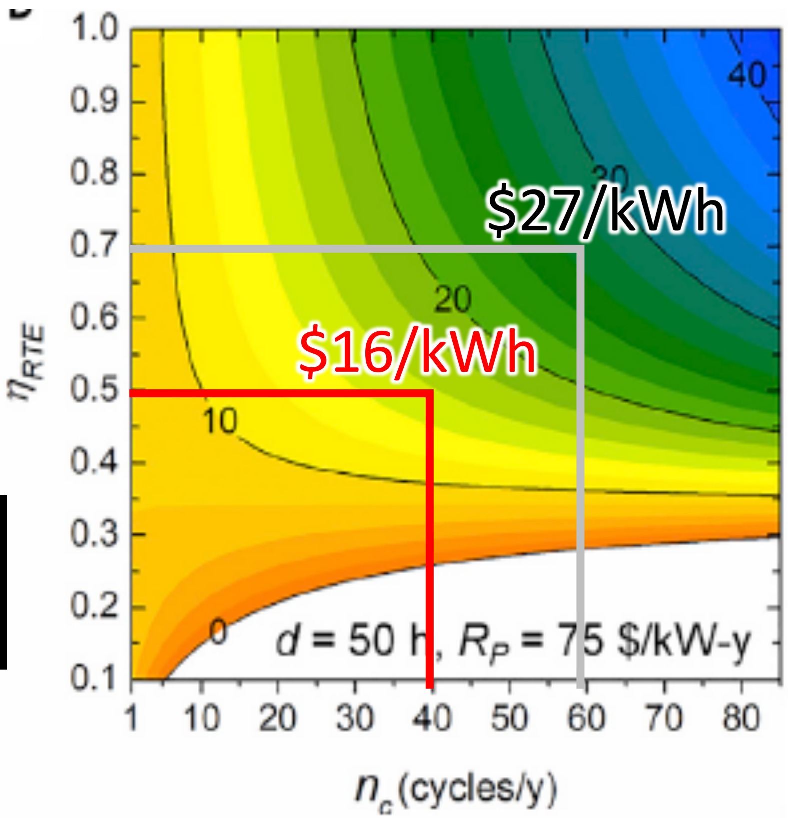


4 GW/hr for 3 hrs

14 GW solar + wind

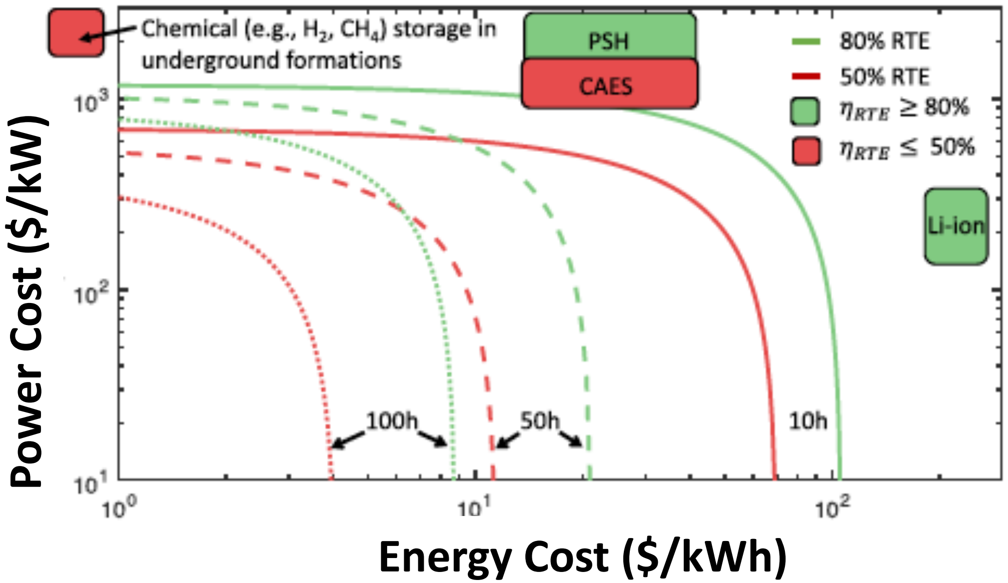


Capital Cost of 50-hr storage



$27/kWh

$16/kWh

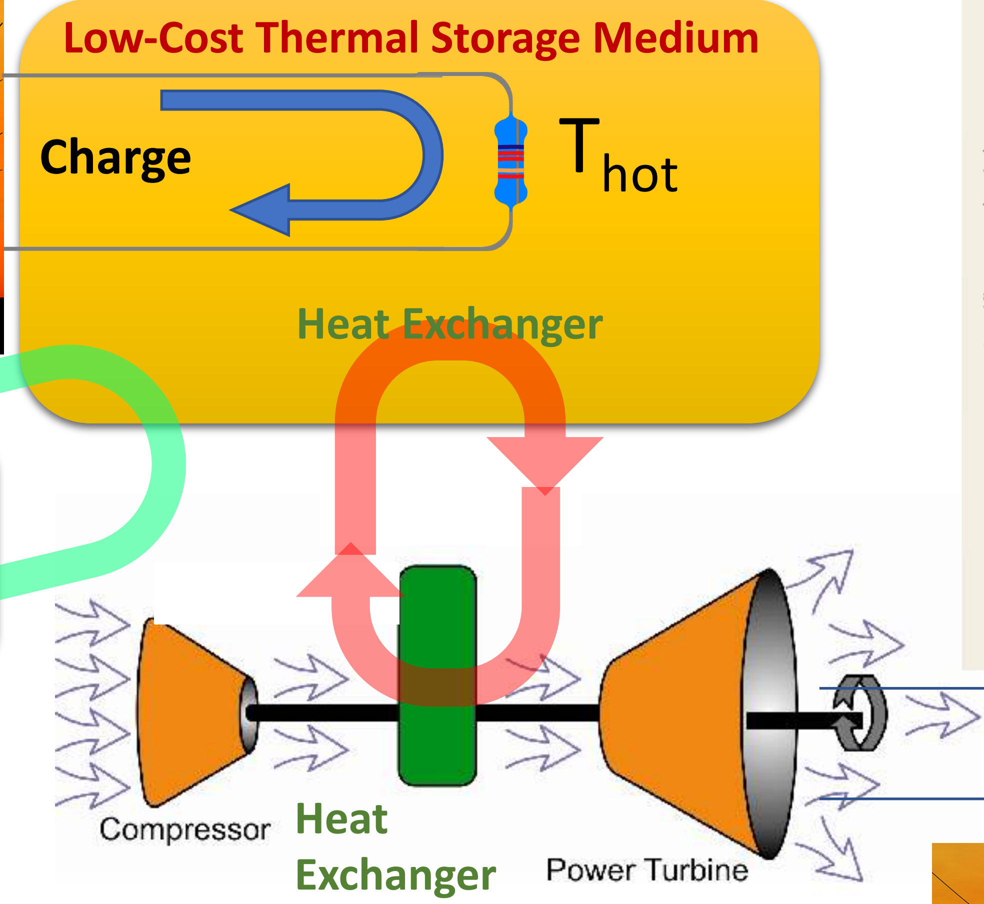


For 100-hr storage
- **$3-10/kWh**

P. Albertus, J.S. Manser, S. Litzelman, "Long-duration electricity storage applications, economics, technology," *Joule* **4**, 21-32 (2020)

Thermal Energy Storage

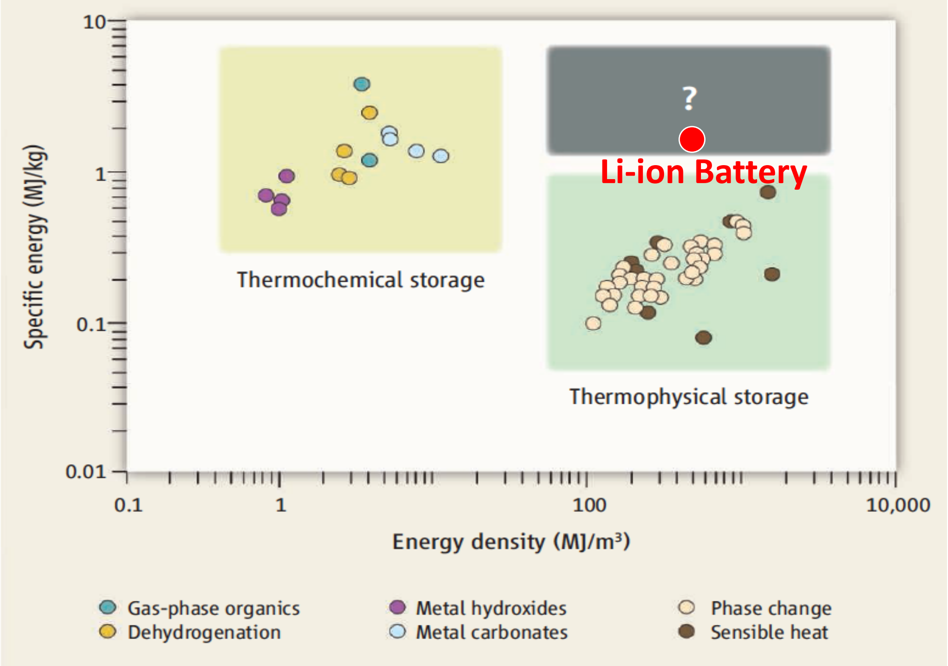
Stanford Campus Energy System



Direct Heat Utilization

(Combined Cycle) Gas Turbine

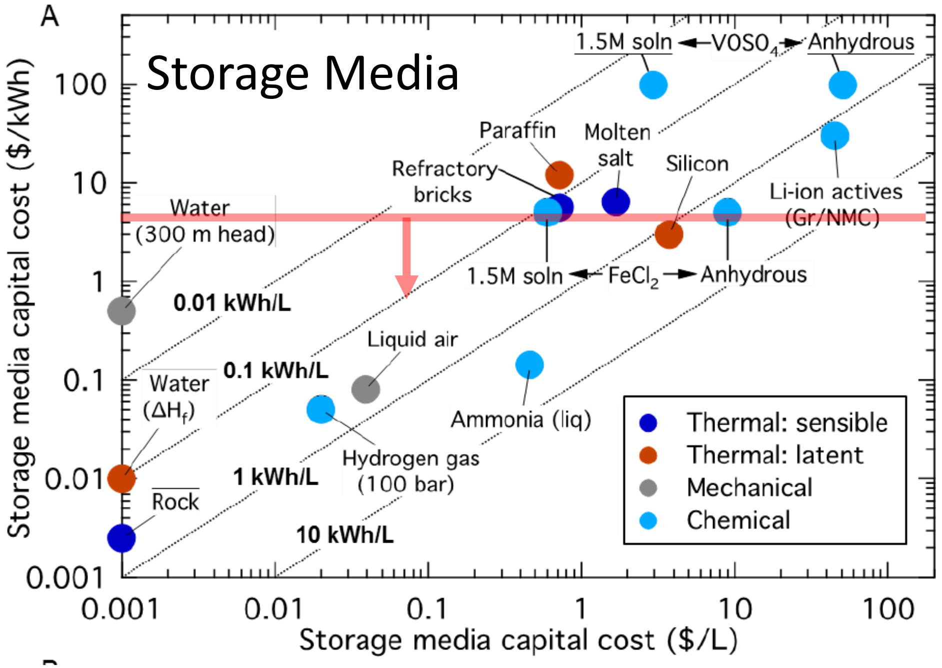
Closed Loop CO_2 Turbine

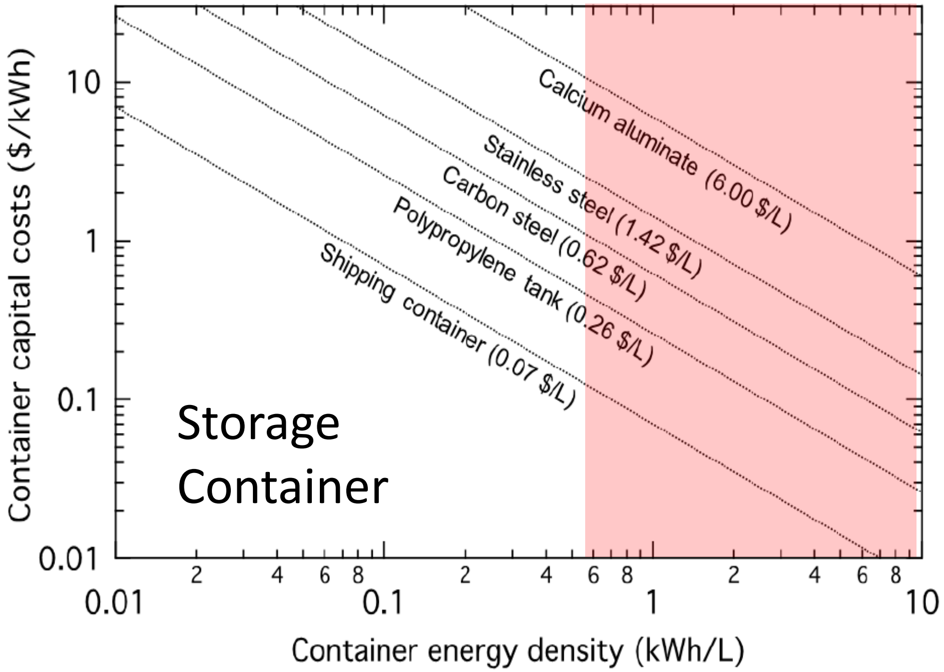


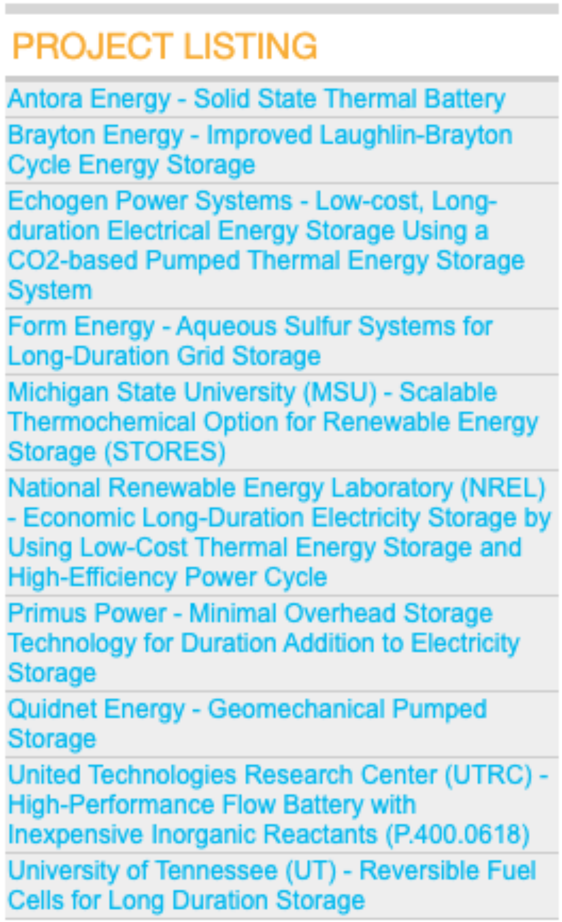
Gur, Sawyer, Prasher, "Searching for a better thermal battery," *Science* **435**, 1454 (2012)

3D Printed Heat Exchangers

ARPA-E DAYS Program







PROJECT LISTING

- Antora Energy - Solid State Thermal Battery
- Brayton Energy - Improved Laughlin-Brayton Cycle Energy Storage
- Echogen Power Systems - Low-cost, Long-duration Electrical Energy Storage Using a CO2-based Pumped Thermal Energy Storage System
- Form Energy - Aqueous Sulfur Systems for Long-Duration Grid Storage
- Michigan State University (MSU) - Scalable Thermochemical Option for Renewable Energy Storage (STORES)
- National Renewable Energy Laboratory (NREL) - Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle
- Primus Power - Minimal Overhead Storage Technology for Duration Addition to Electricity Storage
- Quidnet Energy - Geomechanical Pumped Storage
- United Technologies Research Center (UTRC) - High-Performance Flow Battery with Inexpensive Inorganic Reactants (P.400.0618)
- University of Tennessee (UT) - Reversible Fuel Cells for Long Duration Storage

https://arpa-e.energy.gov/?q=arpa-e-programs/days

Key Technical Challenges

- High Energy Density, Low-Cost Storage Media
- High Heat Transfer Rate

2. Industrial Processes – Cement, Steel, Aluminum, Hydrogen

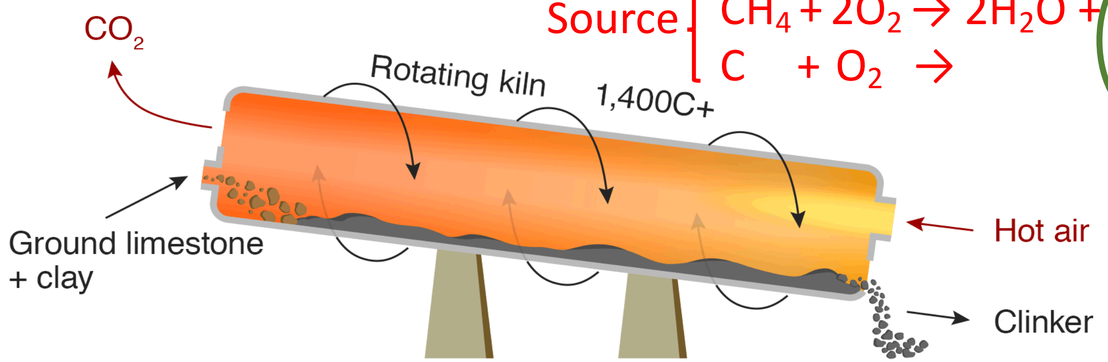
How cement is made

$CaCO_3 \rightarrow CaO + \boxed{CO_2}$ **Pure**

Heat Source

$$\left[\begin{array}{l} CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \\ C + O_2 \rightarrow CO_2 \end{array}\right.$$

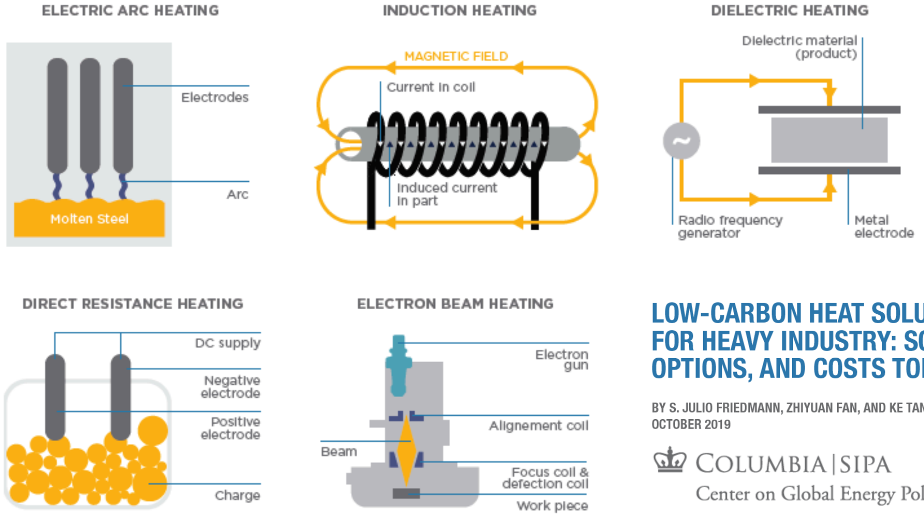
Mixed with N_2



Source: Carbon Brief, Chatham House

BBC

Heating with GHG-Free Electricity



LOW-CARBON HEAT SOLUTIONS FOR HEAVY INDUSTRY: SOURCES, OPTIONS, AND COSTS TODAY

BY S. JULIO FRIEDMANN, ZHIYUAN FAN, AND KE TANG
OCTOBER 2019

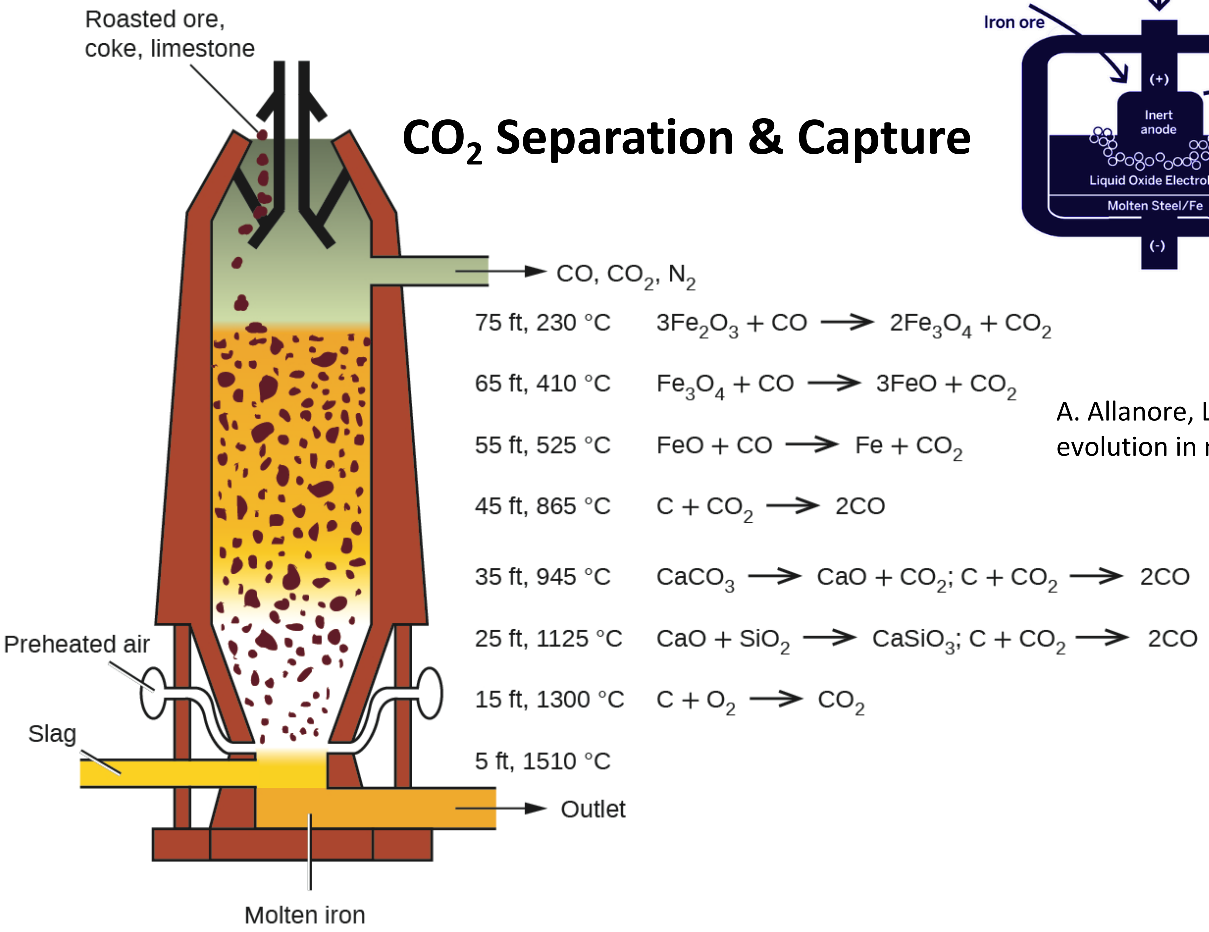
COLUMBIA | SIPA
Center on Global Energy Policy

GHG-Free Hydrogen for Heating

2. Industrial Processes

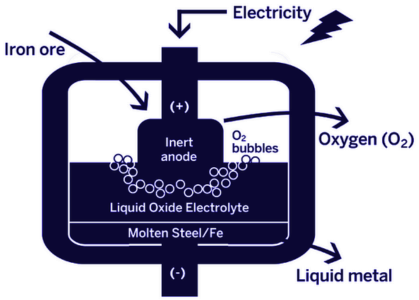
How steel is made

CO_2 Separation & Capture



75 ft, 230 °C	$3Fe_2O_3 + CO \longrightarrow 2Fe_3O_4 + CO_2$
65 ft, 410 °C	$Fe_3O_4 + CO \longrightarrow 3FeO + CO_2$
55 ft, 525 °C	$FeO + CO \longrightarrow Fe + CO_2$
45 ft, 865 °C	$C + CO_2 \longrightarrow 2CO$
35 ft, 945 °C	$CaCO_3 \longrightarrow CaO + CO_2$; $C + CO_2 \longrightarrow 2CO$
25 ft, 1125 °C	$CaO + SiO_2 \longrightarrow CaSiO_3$; $C + CO_2 \longrightarrow 2CO$
15 ft, 1300 °C	$C + O_2 \longrightarrow CO_2$
5 ft, 1510 °C	

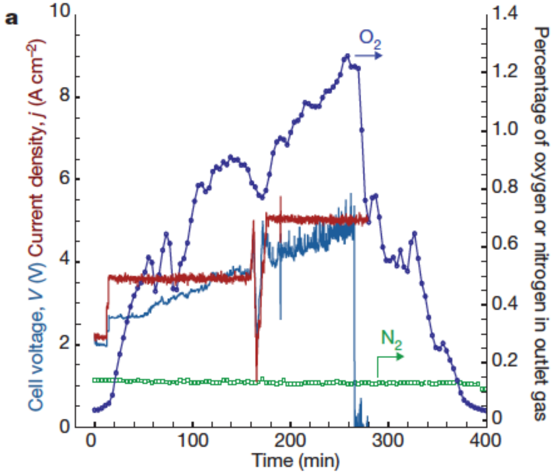
Electrochemical Iron Production



Iron Ore Electricity Iron Oxygen

$$Fe_2O_3 + e^- \rightarrow 2\,Fe + {}^3\!/_2\,O_2$$

Reducing Agent	Electrons
Feedstock	Concentrates or pure oxides
Electrolyte	Molten oxides (CaO, MgO, etc.)
Containment	Refractory or frozen ledge
Temperature	Up to 2,000°C
Product	Pure metals or alloys



$Cr_{90}Fe_{10}$ anode; T = 1565 °C

A. Allanore, L. Yin, D. Sadoway, "A new anode material for oxygen evolution in molten oxide electrolysis," *Nature* **497**, 353 (2013)

Hydrogen Utilization for Heat and Reductant

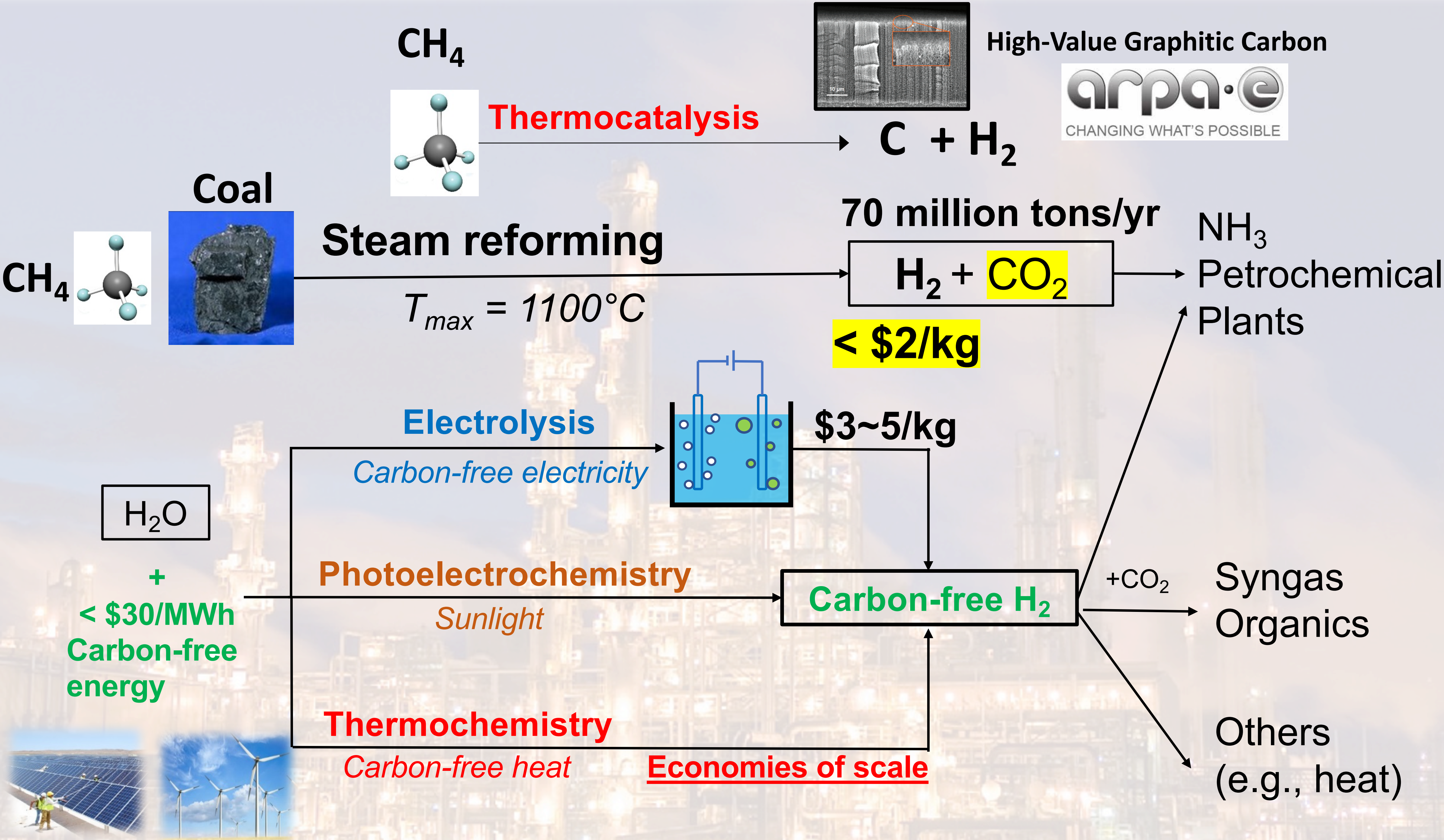
$$Fe_2O_3 + 3H_2 = 2Fe + 3H_2O$$

Challenges

- GHG-free H_2
- Hydrogen Embrittlement

Gigaton-Scale GHG-Free Hydrogen at < $2/kg

20-200 tons per day H_2 plants



CH_4 **Thermocatalysis** → $C + H_2$

High-Value Graphitic Carbon

arpa·e
CHANGING WHAT'S POSSIBLE

CH_4 **Coal** **Steam reforming** → $H_2 + CO_2$ → NH_3 Petrochemical Plants

T_{max} = 1100°C

70 million tons/yr

< $2/kg

H_2O

+

< $30/MWh

Carbon-free energy

Electrolysis

Carbon-free electricity

$3~5/kg

Photoelectrochemistry

Sunlight

Thermochemistry

Carbon-free heat

<u>Economies of scale</u>

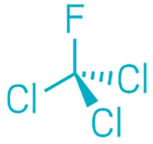
Carbon-free H_2

$+CO_2$

Syngas
Organics

Others
(e.g., heat)

3. Low Global Warming Potential (GWP) Refrigerants



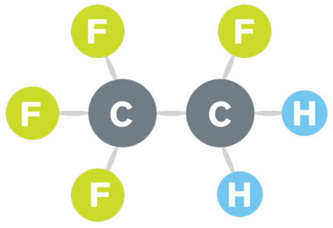
Trichlorofluoromethane (CFC-11)

1987

30 MONTREAL PROTOCOL
caring for all life under the sun

GWP > 2000

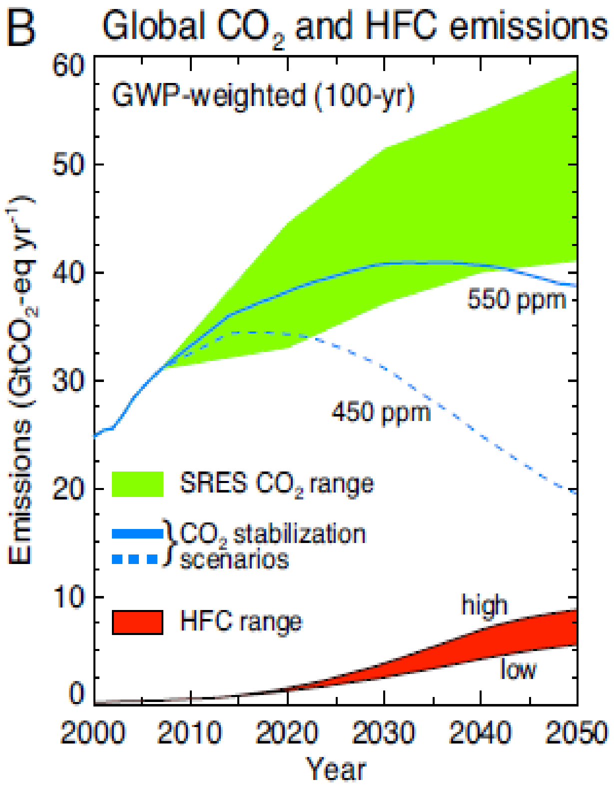
C = Carbon
F = Flourine
H = Hydrogen



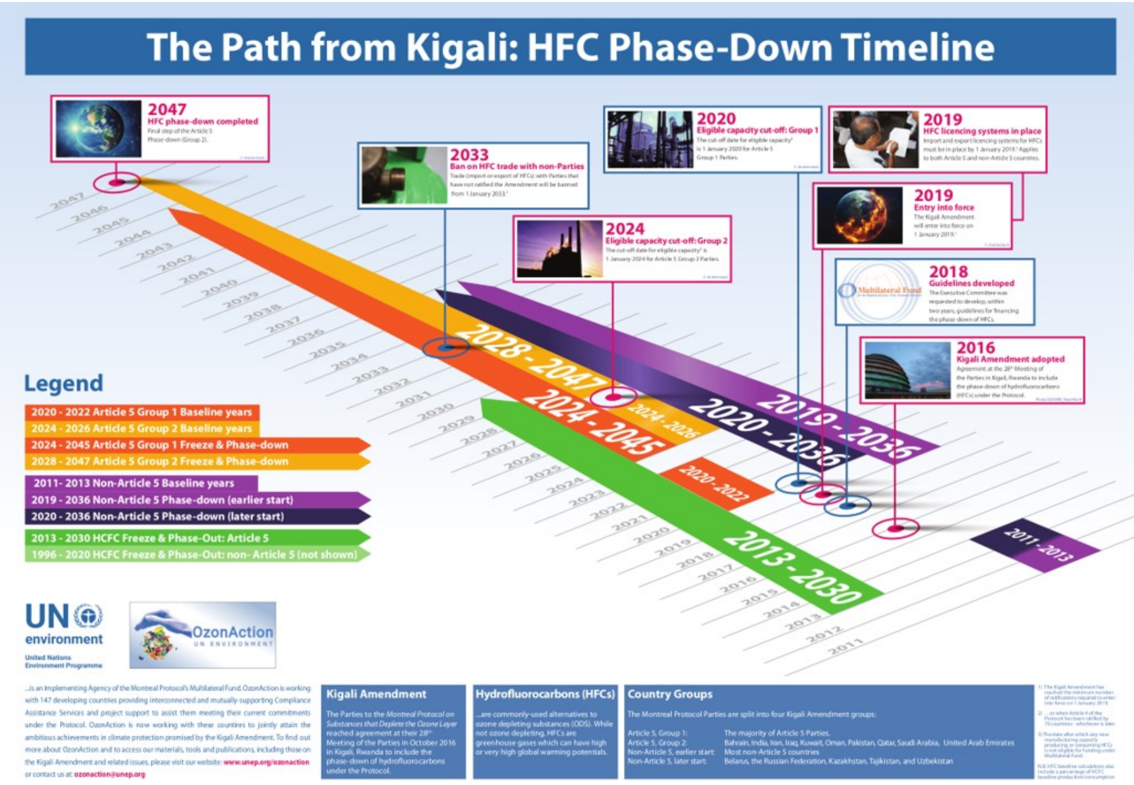
HFC

HFC-134a

REFRIGERANT LEAKAGE



Velders et al., PNAS (2009)



The Path from Kigali: HFC Phase-Down Timeline

2047
HFC phase-down completed
Final step of the Article 5 Phase-down (Group 2).

2033
Ban on HFC trade with non-Parties
Trade (import or export of HFCs) with Parties that have not ratified the Amendment will be banned from 1 January 2033.[2]

2024
Eligible capacity cut-off: Group 2
The cut-off date for eligible capacity[3] is 1 January 2024 for Article 5 Group 2 Parties.

2020
Eligible capacity cut-off: Group 1
The cut-off date for eligible capacity[3] is 1 January 2020 for Article 5 Group 1 Parties.

2019
HFC licencing systems in place
Import and export licencing systems for HFCs must be in place by 1 January 2019.[1] Applies to both Article 5 and non-Article 5 countries.

2019
Entry into force
The Kigali Amendment will enter into force on 1 January 2019.[1]

2018
Guidelines developed
The Executive Committee was requested to develop, within two years, guidelines for financing the phase-down of HFCs.

2016
Kigali Amendment adopted
Agreement at the 28th Meeting of the Parties in Kigali, Rwanda to include the phase-down of hydrofluorocarbons (HFCs) under the Protocol.

Legend

- 2020 - 2022 Article 5 Group 1 Baseline years
- 2024 - 2026 Article 5 Group 2 Baseline years
- 2024 - 2045 Article 5 Group 1 Freeze & Phase-down
- 2028 - 2047 Article 5 Group 2 Freeze & Phase-down
- 2011 - 2013 Non-Article 5 Baseline years
- 2019 - 2036 Non-Article 5 Phase-down (earlier start)
- 2020 - 2036 Non-Article 5 Phase-down (later start)
- 2013 - 2030 HCFC Freeze & Phase-Out: Article 5
- 1996 - 2020 HCFC Freeze & Phase-Out: non- Article 5 (not shown)

UN environment
United Nations Environment Programme

OzonAction
UN ENVIRONMENT

...is an Implementing Agency of the Montreal Protocol's Multilateral Fund. OzonAction is working with 147 developing countries providing interconnected and mutually-supporting Compliance Assistance Services and project support to assist them meeting their current commitments under the Protocol. OzonAction is now working with these countries to jointly attain the ambitious achievements in climate protection promised by the Kigali Amendment. To find out more about OzonAction and to access our materials, tools and publications, including those on the Kigali Amendment and related issues, please visit our website: www.unep.org/ozonaction or contact us at: ozonaction@unep.org

Kigali Amendment

The Parties to the *Montreal Protocol on Substances that Deplete the Ozone Layer* reached agreement at their 28th Meeting of the Parties in October 2016 in Kigali, Rwanda to include the phase-down of hydrofluorocarbons under the Protocol.

Hydrofluorocarbons (HFCs)

...are commonly-used alternatives to ozone depleting substances (ODS). While not ozone depleting, HFCs are greenhouse gases which can have high or very high global warming potentials.

Country Groups

The Montreal Protocol Parties are split into four Kigali Amendment groups:

Article 5, Group 1:	The majority of Article 5 Parties.
Article 5, Group 2:	Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, United Arab Emirates
Non-Article 5, earlier start:	Most non-Article 5 countries
Non-Article 5, later start:	Belarus, the Russian Federation, Kazakhstan, Tajikistan, and Uzbekistan

[1] The Kigali Amendment has reached the minimum number of ratifications required to enter into force on 1 January 2019.

[2] ...or when Article 4 of the Protocol has been ratified by 70 countries - whichever is later.

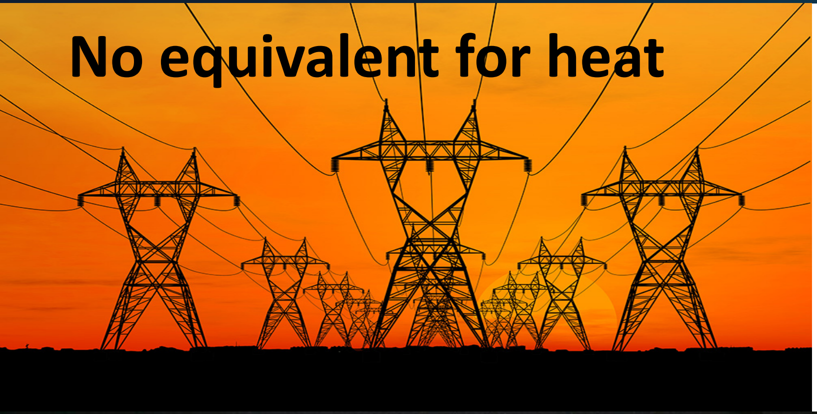
[3] The date after which any new manufacturing capacity producing or consuming HFCs is not eligible for funding under Multilateral Fund.

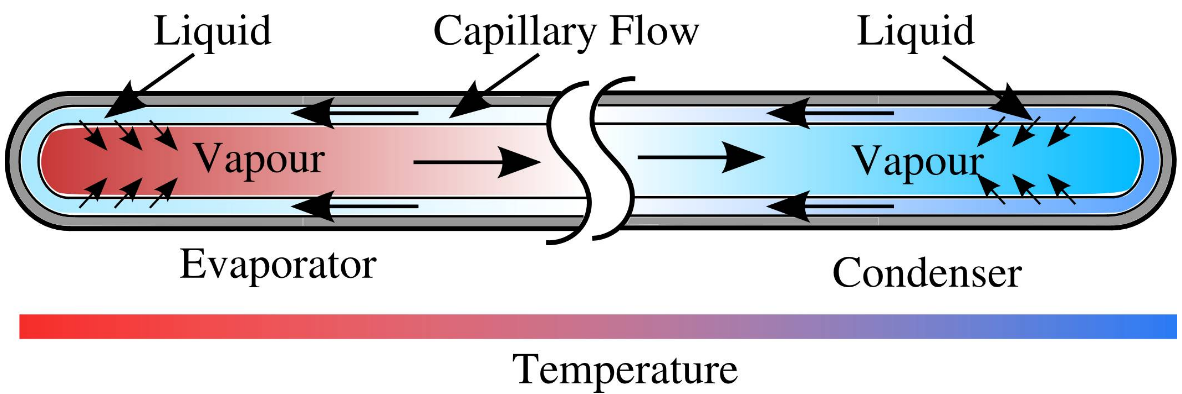
N.B. HFC baseline calculations also include a percentage of HCFC baseline production/consumption.

Can we find a drop-in replacement for HFCs with GWP < 1?

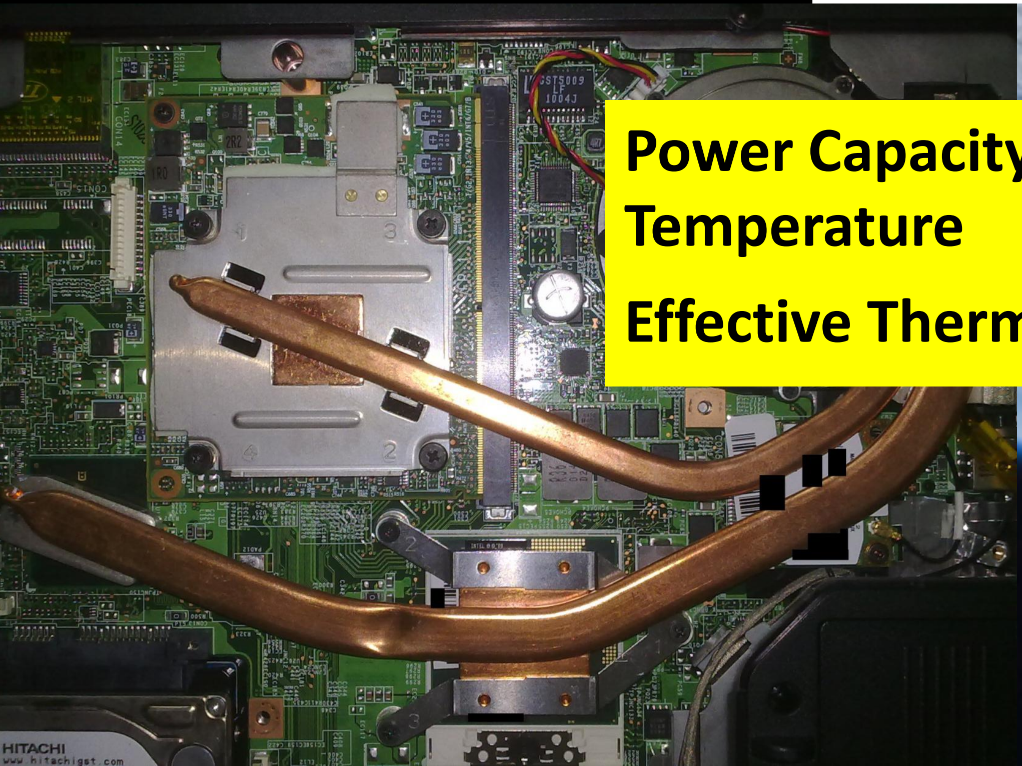
- Non flammanle
- Non toxic
- Affordable

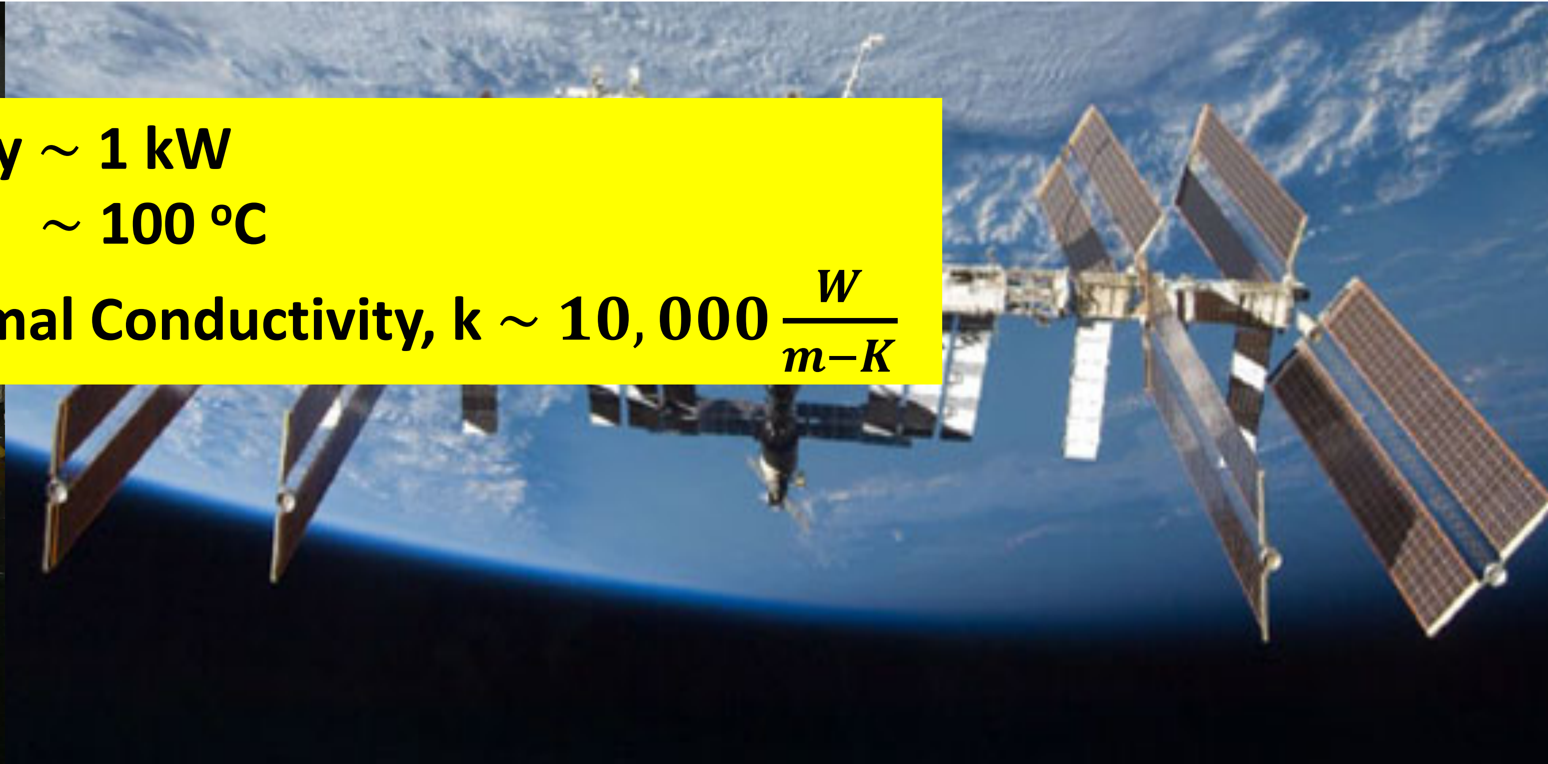
4. Long-Distance Heat Transmission with Low Exergy Loss


No equivalent for heat



Heat Pipe


[redacted]



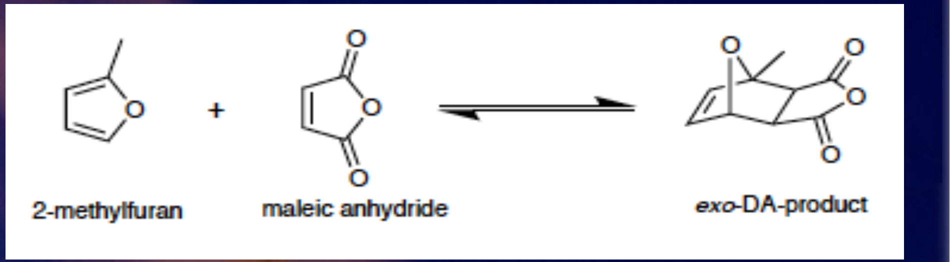
Power Capacity $\sim$ 1 kW

Temperature $\sim$ 100 °C

Effective Thermal Conductivity, k $\sim 10,000\,\frac{W}{m-K}$

Power Capacity ~ 10s MW
Temperature ~ 100-800 ºC
Effective Thermal Conductivity, k $\sim 10,000 \, \frac{W}{m-K}$

Diels-Alder Chemistry



BG Sparks, BE Poling, *AIChE J* **29**, 534 (1983)
P Yu, A Jain, RS Prasher, *NMTE* **23**, 235 (2019)

Dissociative Thermochemical Reaction

$A{:}B \rightarrow A + B$; $\Delta H > 0$

$T = \Delta H / \Delta S$

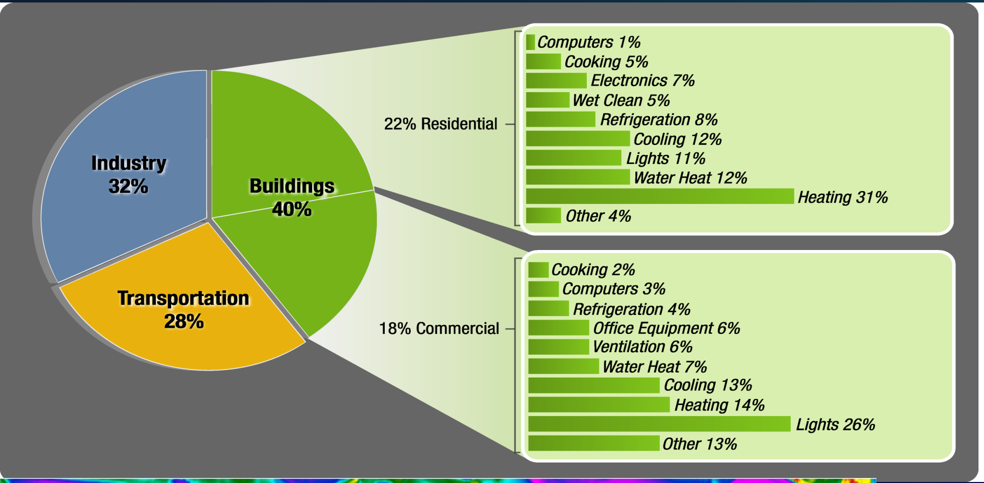
Metal Oxide Redox Reaction

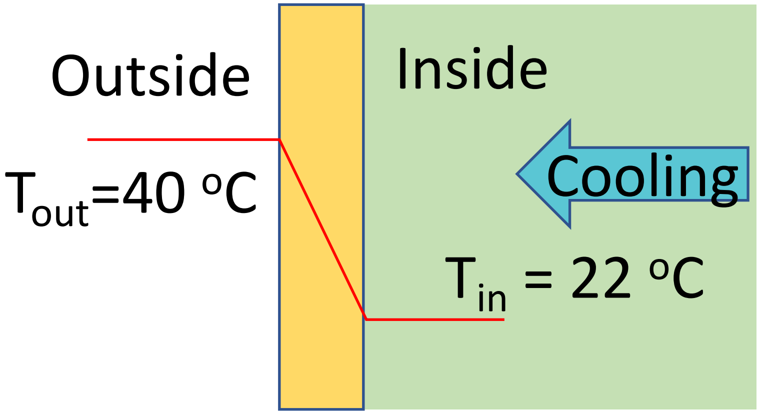
$MO_x \rightarrow MO_{x-a} + ½aO_2$

$CaCO_3 \rightarrow CaO + CO_2$

$A + B \rightarrow A{:}B$; $\Delta H < 0$

5. Variable Thermal Conductance Building Envelopes





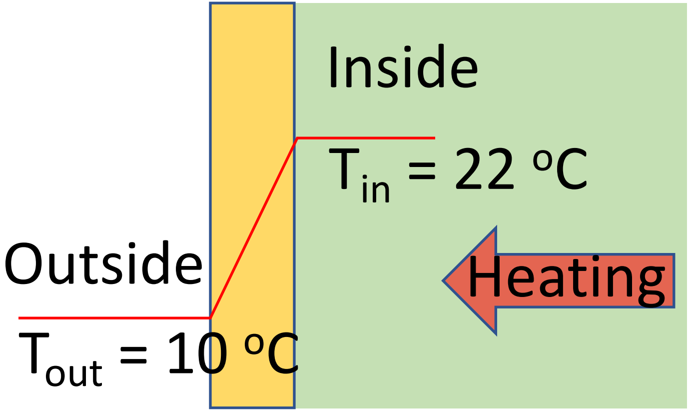
Outside

Inside

T_{out}=40 ºC

Cooling

T_{in} = 22 ºC



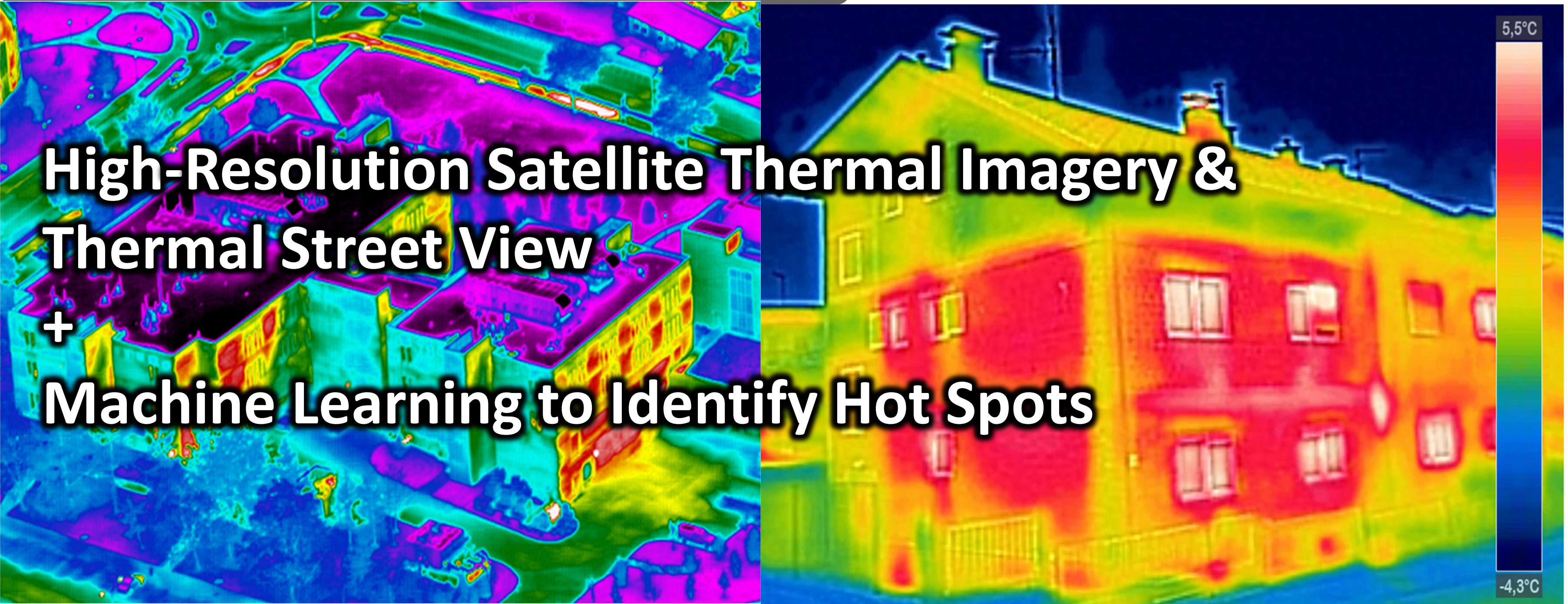
Inside

T_{in} = 22 ºC

Outside

Heating

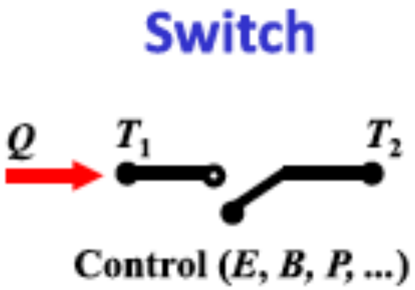
T_{out} = 10 ºC



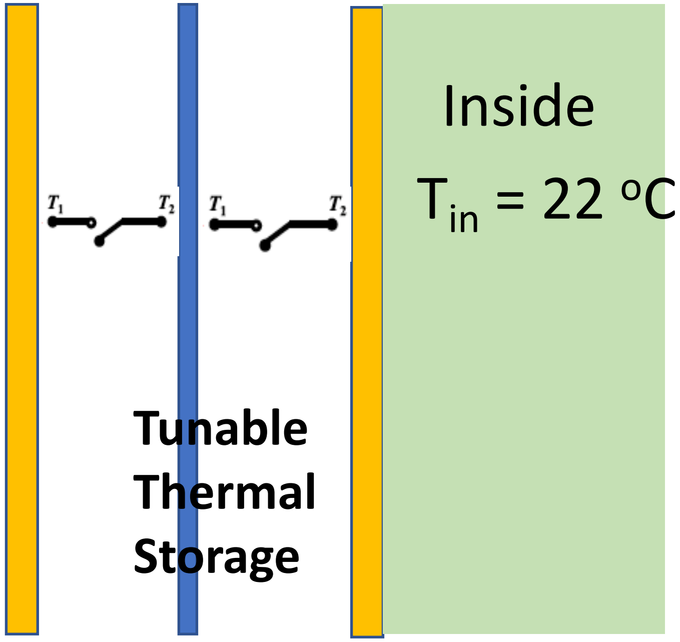
High-Resolution Satellite Thermal Imagery & Thermal Street View
+
Machine Learning to Identify Hot Spots

- Can we control thermal conductance (can save up to 10-40% GHG)?
- Can we couple it with thermal storage?

5. Variable Thermal Conductance Building Envelopes



Wehmeyer, G., Yabuki, T., Monachon, C., Wu, J. & Dames, C. Thermal diodes, regulators, and switches: Physical mechanisms and potential applications. *Applied Physics Reviews* **4**, 041304 (2017)

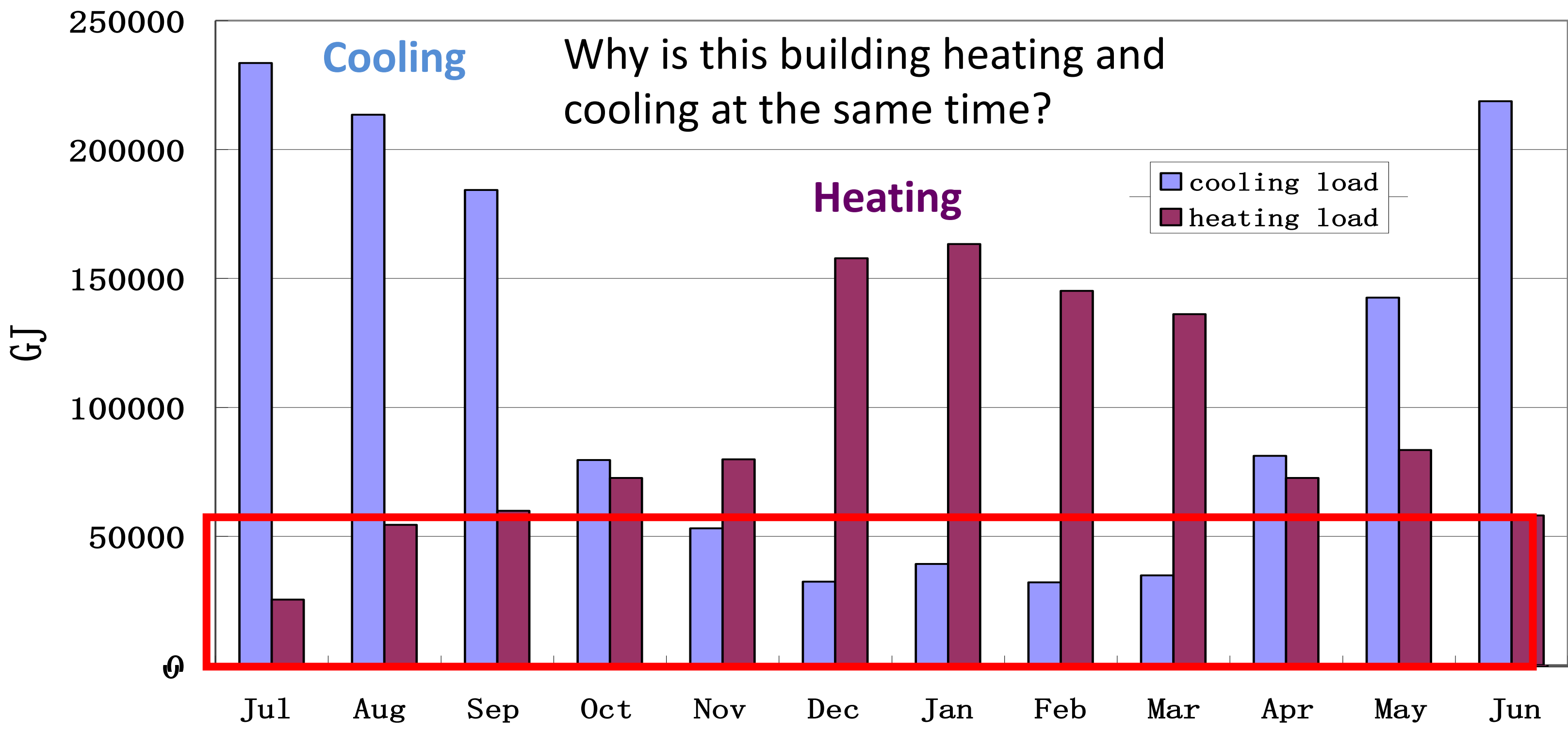


Inside

T_{in} = 22 °C

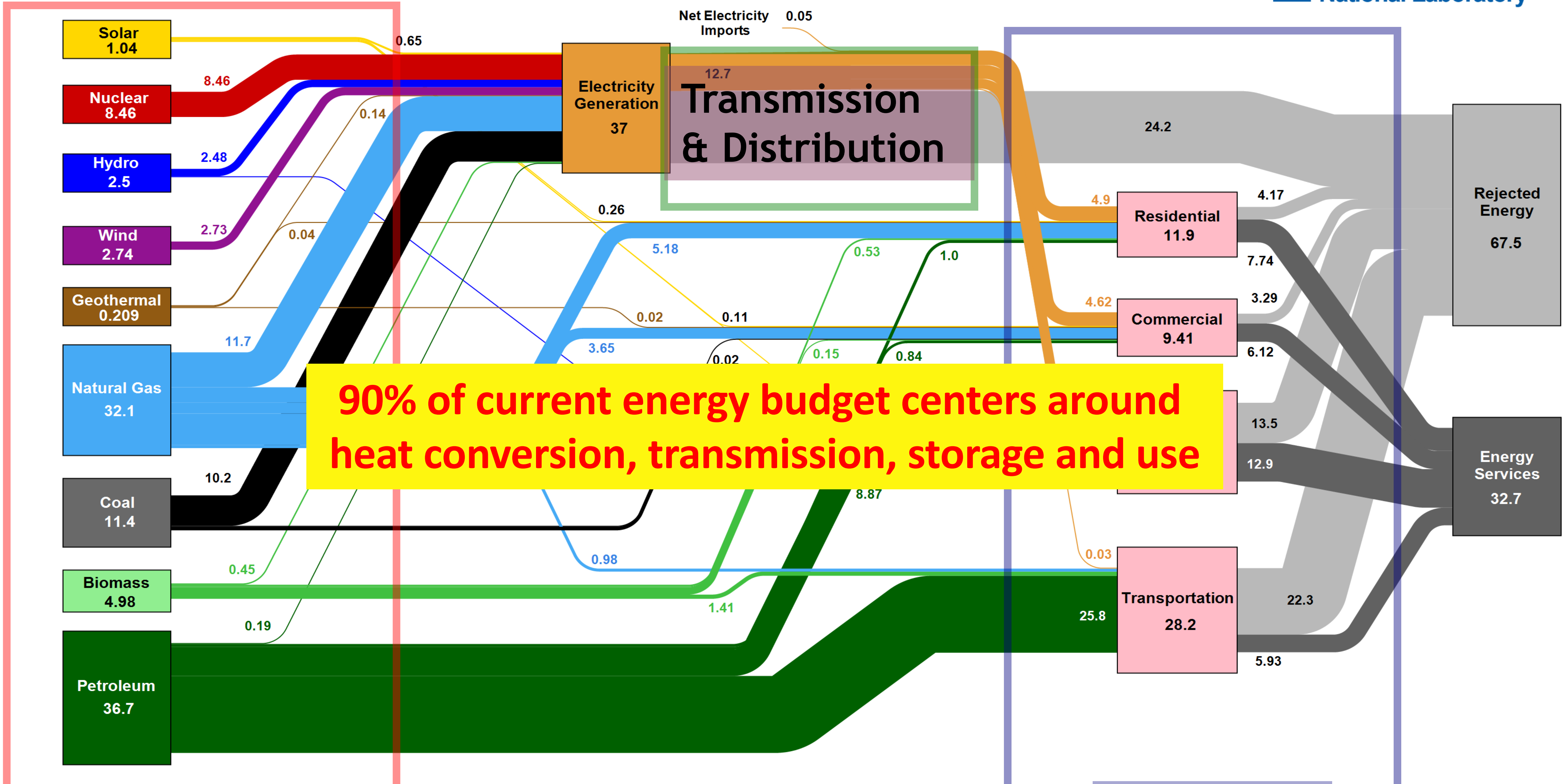
Tunable Thermal Storage

Systems-View of Building Heating & Cooling



Why is this building heating and cooling at the same time?

Estimated U.S. Energy Consumption in 2019: 100.2 Quads



Transmission & Distribution

90% of current energy budget centers around heat conversion, transmission, storage and use

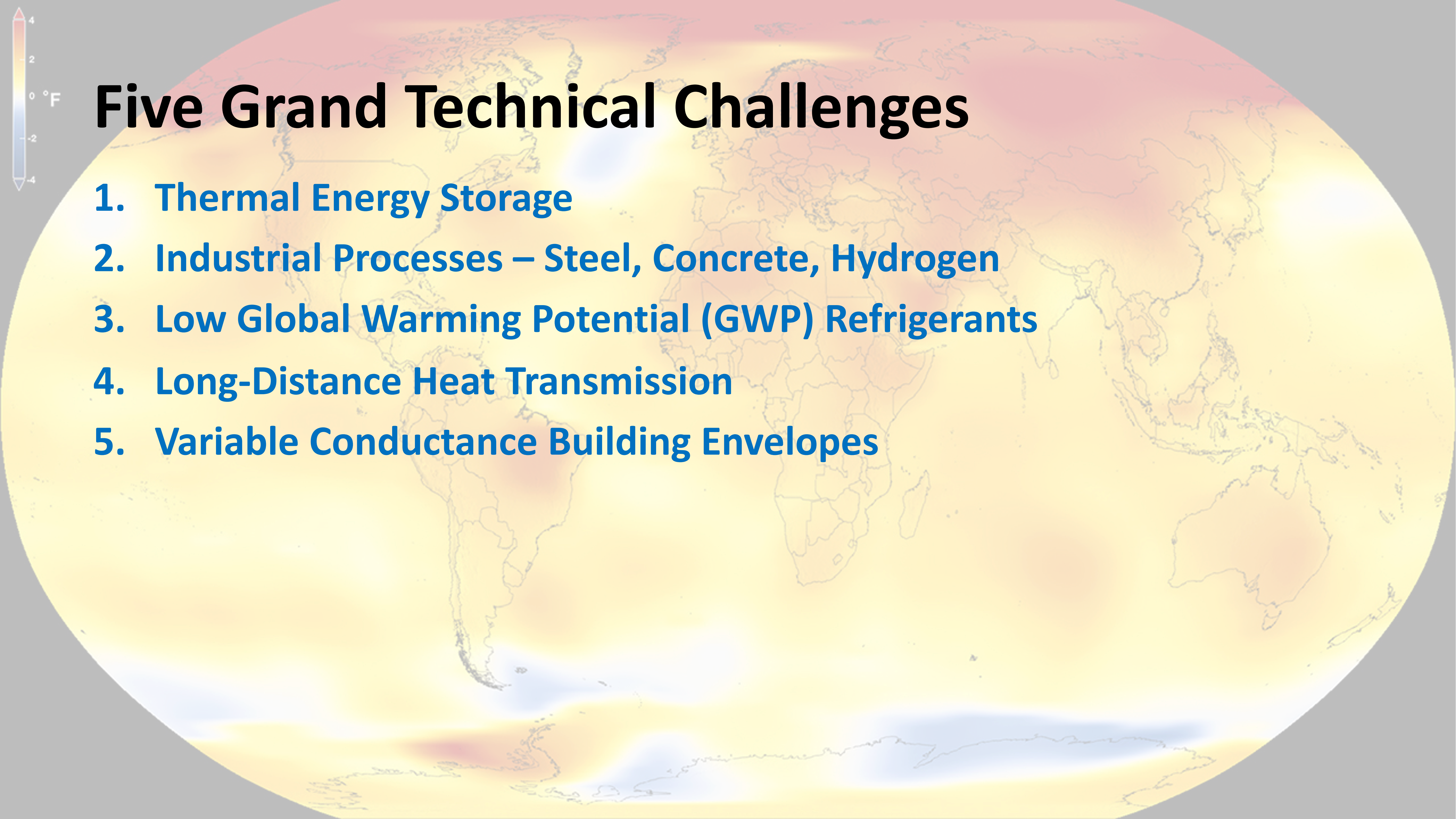
Supply

Demand

Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Five Grand Technical Challenges

1. Thermal Energy Storage
2. Industrial Processes – Steel, Concrete, Hydrogen
3. Low Global Warming Potential (GWP) Refrigerants
4. Long-Distance Heat Transmission
5. Variable Conductance Building Envelopes



Defining the New Normal – Lessons from History

1. Pre-COVID-19 had sustainability challenges on many fronts. COVID-19 has forced us to take a step back.
2. Global economy is in shambles, people are getting sick and some are dying. Many around the world don’t have the luxury to think about the future, but we do. Along with this luxury comes the responsibility to make best use this time. This is a generational responsibility.
3. We (humanity, planet) are all in this together. We need to think and act as the whole, not just pieces at a time.
4. We need to define what the world ought to be post-COVID-19 – **the new normal** - to address the defining dual challenge of the 21st century.
    - Global institutions; policy frameworks; governance; businesses; academia; R&D agenda